

MICROSTRUCTURES WITH ASSISTING OPTICAL LENSES

CROSS-REFERENCE TO RELATED APPLICATIONS

None.

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BACKGROUND OF THE INVENTION

The present invention relates to microfabricated structures to interact with electromagnetic waves and, more particularly to addressable, reusable visual displays. Still more particularly, an embodiment of the invention relates to pre-formed microstructured substrates containing assisting optical lenses to enhance the visual effect of visual displays, such as gyricon displays using rotatable particles (e.g., rotary balls).

For purpose of illustration, the present application uses structures of gyricon displays to demonstrate the concepts and the benefits of the inventive structure.

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A gyricon display, also called a twisting-particle display, rotary ball display, particle display, dipolar particle light valve, etc., is a type of addressable visual displays. A gyricon display offers a technology for making a form of electric paper and other reflective displays. Briefly, a gyricon display is an addressable display made up of a multiplicity of optically anisotropic particles, with each particle being selectively rotatable to present a desired face to an observer. The rotary particle can be of various shapes, such as spherical or cylindrical. For convenience, balls, rather than cylinders, are used in this description for illustrations.

Addressable visual displays typically have multiple display units such as pixels or subpixels. A separate auxiliary optical element is sometimes used in connection with each display to enhance or create certain visual effect. U.S. Patent No. 5,777,782 to Sheridan, for example, discloses a gyricon or rotating-particle display having an auxiliary optical structure which is a pre-formed array of lenses indexed to gyricon particles. Although the Sheridan patent relates to gyricon

displays only, in principle the use of an auxiliary optical structure is not limited to the gyricon displays. A properly designed auxiliary optical structure may be used to enhance or create certain visual effects in other types of visual displays containing multiple display units, such as displays using the electronic ink based on the electrophoretic principle made by E Ink Corp. For purpose of illustration, however, the present application uses structures of gyricon displays to demonstrate the concepts and the benefits of the inventive structure.

A gyricon display, also called a twisting-particle display, rotary ball display, particle display, dipolar particle light valve, etc., offers a technology for making a form of electric paper and other reflective displays. Briefly, a gyricon display is an addressable display made up of a multiplicity of optically anisotropic particles, with each particle being selectively rotatable to present a desired face to an observer. The rotary particle can be of various shapes, such as spherical or cylindrical. For convenience, balls, rather than cylinders, are used in this description for illustrations. Like ordinary paper, electric paper preferably can be written on and erased, can be read in ambient light, and can retain imposed information in the absence of an electric field or other external retaining force. Also like ordinary paper, electric paper preferably can be made in the form of a lightweight, flexible, durable sheet that can be folded or rolled into tubular form about any axis and can be conveniently placed into a shirt or coat pocket and then later retrieved, restraightened, and read substantially without loss of information. Yet unlike ordinary paper, electric paper preferably can be used to display full-motion and changing images as well as still images and text. Thus, it is particularly useful for bistable displays where real-time imagery is not essential, but also adaptable for use in real-time imaging such as a computer display screen or a television.

In the prior art, the black-and-white balls (particles) are embedded in a sheet of optically transparent material, such as an elastomer sheet. The elastomer sheet is then cured. After curing, the elastomer sheet is placed in a

plasticizer liquid, such as a dielectric fluid. The dielectric plasticizer swells the elastomer sheet containing the particles creating cavities larger than the particles around the particles. The cavities are also filled with the absorbed dielectric fluid. The fluid-filled cavities accommodate the particles, one particle per cavity, so as to prevent the particles from migrating within the sheet.

Besides being optically anisotropic, the particles are electrically dipolar in the presence of the fluid. This may be accomplished by simply including in one or both hemispheres materials that impart an electrical anisotropy, or by coating one or both sides of hemispheres with materials that impart electrical anisotropy. The above charge activation agents may impart an electrical anisotropy and an optical anisotropy at the same time. For example, when each hemisphere of a gyrricon particle is coated with a material of a distinct electrical characteristic (e.g., Zeta potential with respect to a dielectric fluid) corresponding to a distinct optical characteristic the particles will have an electrical anisotropy in addition to their optical anisotropy when dispersed in a dielectric liquid. It is so because when dispersed in a dielectric liquid the particles acquire an electric charge related to the Zeta potential of their surface coating.

An optically anisotropic particle can be selectively rotated within its respective fluid-filled cavity, for example by application of an electric field, so as to present either its black or white hemisphere to an observer viewing the surface of the sheet. Under the action of an addressing electric field, such as provided by a conventional matrix addressing scheme, selected ones of the optically and electrically anisotropic particles are made to rotate or otherwise shift their orientation within their cavities to provide a display by the selective absorption and reflection of ambient light. Since the particles need only rotate, not translate, to provide an image, much faster imaging response is achieved than with the display of U.S. Patent No. 3,612,758.

When the electric field is applied to the sheet, the adhesion of each particle to the cavity is overcome and the particles are rotated to point either their black or white hemispheres towards the transparent surface. Even after the electric field is removed, the structures (particles in specific orientations) will stay in position and thus create a bistable display until the particles are dislodged by another electric field. An image is formed by the pattern collectively created by each individual black and white hemisphere. Thus, by the application of an electric field addressable in two dimensions (as by a matrix addressing scheme), the black and white sides of the particles can be caused to appear as the image elements (e.g., pixels or subpixels) of a displayed image. These bistable displays are particularly useful for remotely addressable displays that require little power to switch and no power to maintain display image for a long period of time (e.g., months).

Gyricon display technology is described further in U.S. Patent No. 4,126,854 (Sheridon, "Twisting Ball Panel Display") and U.S. Patent No. 5,389,945 (Sheridon, "Writing System Including Paper-Like Digitally Addressed Media and Addressing Device Therefor"). Further advances in black and white gyricon displays have been described in U.S. Patent No. 6,055,091 (Sheridon, "Twisting-Cylinder Display"). The above-identified patents are all hereby incorporated by reference. The Sheridan patents disclosed a gyricon display which uses substantially cylindrical bichromal particles rotatably disposed in a substrate. The twisting cylinder display has certain advantages over the rotating ball gyricon because the elements can achieve a much higher packing density. The higher packing density leads to improvements in the brightness of the twisting cylinder display as compared to the rotating ball gyricon.

Gyricon displays are not limited to black and white images, as gyricon and other display mediums are known in the art to have incorporated color. Gyricons incorporating color have been described in U.S. Patent No. 5,760,761 titled "Highlight Color Twisting Ball Display", U.S. Patent No. 5,751,268 titled "Pseudo-

Four Color Twisting Ball Display”, U.S. Patent Application Serial No. 08/572,820
titled “Additive Color Transmissive Twisting Ball Display”, U.S. Patent Application
Serial No. 08/572,780 titled “Subtractive Color Twisting Ball Display”, U.S. Patent
No. 5,737,115 titled “Additive Color Tristate Light Valve Twisting Ball Display”,
5 U.S. Patent No. 6,128,124 titled “Additive Color Electric Paper Without
Registration or Alignment of Individual Elements” and European Patent No.
EP0902410 titled “Methods for Making Spinnable Ball, Display Medium and
Display Device”. The above-identified patents are all hereby incorporated by
reference.

10 The above prior art all involve a process which is to randomly pack
the bichromal particles in an elastomeric matrix, cure the elastomer, and
subsequently swell the elastomer in the dielectric oil. The process is laborious and
time-consuming, consisting of mixing of the particles into the elastomer, coating the
slurry into a sheet format, curing, and subsequently swelling the sheet with the
15 dielectric oil.

Furthermore, the display device of such an arrangement poses
problems in connection with the selection of a usable dielectric liquid, stability upon
changes in temperature, non-uniformity of dimensions of the cavities, and the like.
The material considerations in the prior art are many, the primary issues being
20 tuning the swelling of the elastomer by the dielectric oil without harming the
dielectric oil compatibility with all the other elements of the display package.

Furthermore, the above approach resulted in less than satisfactory
contrast of the display, associated with the relatively low reflectance of a gyricon
display. It is commonly believed that the best way to improve the reflectance of a
25 gyricon display is to make the display from a close packed arrangement of
bichromal particles. The closer packed the arrangement of particles, the better the
reflectance and the brighter the appearance of the display. To achieve a close
packed arrangement, the cavities in which the particles rotate should be close to

each other and each cavity should have little unfilled space when filled with a particle, ideally no more empty space than what is necessary to keep the particle therein rotatable. The prior art approaches, however, had difficulties to achieve a high density of particles, mainly due to the lack of controlling on the formation of individual cavities. The result is typically that cavities are either too large, or distributed too loosely in the elastomer with large distances and thick walls between the individual cavities, making it difficult to control the arrangement and packing density of the display particle members to a sufficiently high value to achieve a display of high quality, high resolution, and high contrast.

As a related problem, in a typical conventional gyricon display, bichromal particles are dispersed throughout the thickness of the substrate sheet, which is always thicker than two particle diameters and is usually many diameters thick. Generally, less than 20 percent of the upper surface area of the sheet is covered by the bichromal particles in the layer closest to the surface. Therefore, a display according to the above prior art has multiple layers of particles instead of a single layer, making the display thick and bulky, an undesirable feature especially for an electronic paper. In the prior art designs, the multiple layer configuration is on one hand necessary in order to increase the reflectance (the reflectance of multiple layers of loosely packed particles accumulatively approaches that of a closely packed single layer) and on the other hand difficult to avoid due to the characteristics of the prior art process of making a display.

To achieve higher packing density, the above method was modified in U.S. Patent No. 4,438,160 to Ishikawa et al, which patent is hereby incorporated preference. In the Ishikawa patent, instead of using the swelling method to create cavities larger than the particles, the particles are coated with a layer of wax before being placed in the elastomer. The wax is later melted away, resulting in cavities that are larger than the particles. Presumably, because it is easier to control the thickness of the wax layer coated on the particles than to control the degree of

swelling the elastomer, it is also easier to achieve higher density of particles by using the Ishikawa method. The actual improvement, however, is not significant enough to solve the problem. See U.S. Patent No. 5,825,529 to Crowley, which patent is hereby incorporated by reference.

5 To achieve still higher packing density, a gyricon display can be constructed without elastomer and without cavities. U.S. Patent No. 5,825,529 to Crowley, for example, uses no elastomer substrate. In the display in the Crowley patent, the bichromal particles are placed directly in the dielectric fluid. The particles and the dielectric fluid are then sandwiched between two retaining
10 members (e.g., between the addressing electrodes). There is no elastomer substrate. Electrodes serve both to address particles and to retain particles and fluid in place. Particles and fluid can be sealed in the display by seals at either end of the display. In addition, the spacing between electrodes is set to be as close to the diameter of particles as is possible consistent with proper particle rotation, resulting a monolayer
15 display. The Crowley patent achieved a display with a closely packed monolayer having a light reflectance that surpasses that of the multi-layer displays in the prior art. The display in Crowley, however, achieves a higher packing density by sacrificing structural integrity. The Crowley display lacks internal support and has insufficient sealing. Particularly, the display will not work when placed vertically.

20 More fundamentally, even with the above improved methods making twisting particle displays the particles cannot be packed together to completely fill the area of the display because of the existence of interstices. Furthermore, regardless of which microstructure is used, and regardless of how the particles are packed, the particles often do not exactly rotate to the precise orientation to have
25 only the side with the desired optical characteristics facing the viewer. Both partial filling and partial rotating contribute to decreased image contrast in the following manner: Gyricon displays use optically anisotropic particles that are selectively rotatable to communicate visual information. For example, in a display using

bichromal spherical balls where each ball defines a display unit which conveys the characteristic color information of the spherical ball's hemisphere which is selectively turned to face the viewer, the unit display area is typically the projection area or image size of the ball. Due to the unfilled spaces between the particles and
 5 also due to imperfect rotation which may show wrong color or portions of contrasting (hence cancelling) colors, each particle is surrounded by a peripheral area which does not carry any color information of the particle selectively rotated. Instead the peripheral area substantially reflects the optical characteristic of the substrate which is typically dark. This phenomenon causes decreased contrast. The
 10 same phenomenon exists in displays where each unit display is defined by multiple particles.

The auxiliary optical structure in U.S. Patent No. 5,777,782 to Sheridan is not used to solve the above identified low contrast problem. Rather it is used to focus a visual element of gyricon particles to form a projected image on
 15 the other side of the transmissive gyricon display. Furthermore, the auxiliary optical structure in that patent is a pre-formed array of fly's-eye lenses which need to be then precisely aligned in each of x, y and z directions with the gyricon particles. Such requirement of alignment or indexation between a pre-formed array of lenses and a separately formed gyricon display structure is difficult and costly.

20 BRIEF SUMMARY OF THE INVENTION

The present invention uses assisting optical elements to enhance or improve optical effect of a microstructure, such as contrast of visual displays (e.g., a gyricon display). To enhance contrast of a visual display, for example, an assisting optical element is placed over or around each display unit to form an enlarged image
 25 of at least a portion of the upper side of the display elements (such as the gyricon particles) in that display unit so that the effective unit display area is larger than the actual unit display area, therefore diminishing the effect of imperfect orientation of the display elements and dark peripheral effect caused by the substrate.

The assisting optical elements may be either reflective or refractive. In one preferred embodiment, optical lenses are directly fabricated on the substrate containing the display elements (such as gyricon particles). The lenses form enlarged images of the surface of each particle when viewed from above. The inventive assisting lens structure in accordance with the present invention is not pre-formed separately from the substrate and the display elements. Instead the lenses are formed directly on the substrate corresponding to the geometric shapes and positions of the cavities on the substrate. Because the display elements are contained in the cavities, each lens is "custom-formed" based on the location of the display element or display elements in the associated cavity, and no indexing is required. That is, in contrast to the pre-formed fly's eye lens structure, the inventive assisting lenses are directly formed on the underlying substrate resulting in automatic indexing or registration between the lenses and the corresponding display units.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be further explained with reference to the drawing figures listed below, wherein like structure is referred to by like numerals throughout the several views.

FIG. 1A is a side sectional view of a monolayer black and white gyricon display according to the present invention where the display comprises a plurality of similar or identical display units.

FIG. 1B is a partial top view of the display in FIG. 1.

FIG. 2 is a side sectional view of a single display unit in an embodiment according to the present invention where the assisting optical element includes a converging lens.

FIG. 3 illustrates a first step used to form the lenses in the embodiment of FIG. 2.

FIG. 4 illustrates a second step used to form the lenses in the embodiment of FIG. 2.

While the above-identified drawing figures set forth several preferred embodiments of the invention, other embodiments are also contemplated, as noted in the discussion. In all cases, this disclosure presents the present invention by way of representation and not limitation. It should be understood that numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope and spirit of the principles of this invention.

DETAILED DESCRIPTION

1. General Aspects of the Invention

The invention will now be described with reference to the drawings. For convenience, the drawing figures depict a reflective gyricon display with each optical element being associated with one spheroidal gyricon particle. The inventive structure in accordance with the present invention, however, may also be used to enhance or create certain optical effects in other types of microstructures. Generally, any microstructure that contains an element having a certain optical aspect by modulating or interacting with an incident electromagnetic wave and giving rise to an identifiable optical effect may use the assisting optical element of the present invention to improve or enhance the optical effect. For example, where elements having optical aspects pertaining to electromagnetic waves other than a visible light are used, the inventive microstructure may be used as a device for optical purposes other than visual displays. Examples for such applications include but are not limited to microwave reflectors and absorbers, IR reflectors and absorbers, and configurable radio wave antennas and reflectors. In the case where the electromagnetic wave is a visible light, applications of the present invention include but not limited to visual displays using microstructures containing a display element. A display element can be anything that carries certain visual information.

Particularly, the element having an optical aspect may be optically anisotropic (i.e., having two or more optical aspects) and capable of switching among the optical aspects in response to external signal. The twisting particles or rotating balls used in gyricon displays are examples of such responsive elements
5 having an optical anisotropy.

Visual displays that may use the inventive lens structure typically contain multiple display units, each display unit including one or more responsive elements as display elements. Besides gyricon displays, examples of such visual displays include but not be limited to displays based on the electrophoretic principle
10 such as electronic ink made by E Ink Corp.

Furthermore, when used with a gyricon display, the inventive lens structure is not limited to uses with reflective gyricon displays but may also be used with a transmissive gyricon display or a retroreflective gyricon display. In addition, each assisting optical element may be associated with a display unit that consists of
15 multiple gyricon particles, and the particles may be of geometric shapes other than balls. As described in U.S. Patent Nos. 4,126,854; 5,389,945; 6,055,091; and 6,128,124 and European Patent No. EP0902410, which patents are hereby incorporated herein by reference, when a gyricon display is addressed using electrodes, the display consists of multiple pixels of certain desired density, each
20 pixel being distinguished from other pixels by its addressing. In the case of a color display, each pixel further consists of multiple subpixels (generally three subpixels, each representing an elemental color). Each pixel or subpixel may consist of a single gyricon particle, or multiple gyricon particles. Unless specified otherwise in the context, the present application uses the term "display unit" to present a unit on
25 the display substrate containing a single particle or a group of particles in which group the displays of the particles are addressed in an additive mode (i.e., the display of each particle is designed to be mixed with the displays of the rest of the

particles in the same group). Such a group may be a pixel in a black-and-white display, or either a pixel or a subpixel in a color display.

With reference to FIG. 1A, a gyricon display **2** comprises a plurality of repetitive display units **4**. Each display unit comprises a gyricon particle **6** (a spherical ball as shown), an optical lens **38** and a portion of substrate **9**. Each particle **6** has two optically distinct sides **6a**, **6b**, one facing the viewer (not shown) above and the other facing away from the viewer.

With reference to FIG. 1B, a viewer from above (not shown) sees an top image of each display unit **4**. When an optically anisotropic particle **6** is selectively rotated, the side facing the viewer has a dominant color. This is often true even if the rotation is imperfect to a certain extent. Without assistance of the optical lens **38**, each display unit **6** has an effective display area **A** which is typically the projection area or image size of the ball. Due to the unfilled spaces between the particles, each particle is surrounded by a peripheral area **B**. Without assistance of an assisting optical element, the peripheral area **B** does not carry any color information of the particle selectively rotated, instead it reflects the optical characteristic of the substrate which is typically dark. Where the peripheral area **B** is substantial as compared to display area **A**, contrast of the display decreases. In addition, incomplete or over rotation also lowers contrast by contributing to area **B** due to showing portions of contrasting colors instead of a single dominant color.

The optical lens **38** helps to enhance the contrast. With the optical lens **38**, the dominant color of the particle side facing the viewer is spread or diffused into the peripheral area through refraction. As a result, when viewed through the assisting optical element, the viewer sees an image of the display unit larger than the actual size of the particle. The enlarged image has the same dominant color as that of top side **6a** of the corresponding particle and diminishes the image-derogating effect caused by the peripheral area **B**.

In addition to contrast enhancement, other display qualities such as a wider viewing angle or a wider incident light receiving angle may be achieved by engineering various proper optics.

Description of preferred embodiments according to the spirit of the invention follows.

2. Preferred Embodiments

With reference to FIG. 2, a single display unit 4 in an embodiment according to the present invention includes a converging lens 38 disposed at the top perimeter edge 37 of the cavity 33. The converging lens 38 forms an enlarged image of the upper portion (white hemisphere 6a as shown) of the ball 6 as explained below.

When placed properly in relation to an object, a converging lens may form an enlarged image of the object. When the object is placed within the focus length of the converging lens, for example, the viewer from the other side of the lens will see an enlarged image of the object formed on the same side as the object relative to the lens. With reference to FIG. 2, light 35 from a top portion 14 is refracted through the converging lens 38 before reaches the viewer from above (not shown). If, for example, the top hemisphere 6a of the ball 6 is located within the focal length of the converging lens 38, an enlarged image of the top hemisphere 6a will be formed on the same side as the ball 6 (i.e., the opposite side to the viewing side) relative to the lens to the viewer from above.

If the enlargement is sufficient to cover a substantial amount of the peripheral area around the ball 6, the contrast of the display will be enhanced. The amount of enlargement, however, should not be excessive. An over-enlarged image starts to blur with the images of adjacent balls 6 and will lead to decreased resolution of the display.

The degree of enlargement is determined by the focal length of the converging lenses 38 and the distance between the top hemisphere 6a and the lens 38. The maximum amount of enlargement without blurring the display is determined by the size of the peripheral area around each ball 6. To optimize the display, it is therefore important to be able to control the focal length of the lenses 38 and the sizes of the cavities 3 in the process of manufacturing the display.

In FIG. 2, the converging lens 38 is spaced from the rotating ball 6 and the space therebetween is filled with entrapped air (not shown). Alternatively, a transparent filler material 12 may be used. Besides being an optional support for the lens 38, the filler material 12, when properly selected and applied, helps to create bistability of the gyricon particles 6.

The cavity 33 has a smooth and continuous conical shape. Alternatively, other geometric shapes of the cavity 33, such as the two-portion design in FIG. 2 and FIG. 3 of the commonly-owned U.S. patent application titled “Microstructures with Assisting Optical Elements to Enhance an Optical Effect” and filed concurrently (Attorney Docket Number M507.12-16) may be used. The disclosure of the above-identified patent application is hereby incorporated herein by reference. Conversely, the assisting optical elements illustrated in that application may also be combined with the converging lens 38 this application. Additionally, the partial enclosing design illustrated in FIG. 3 of that application may also be used in the converging lens model as shown in FIG. 2 in this application.

FIG. 2 and FIG. 3 both illustrate a single display unit. The actual visual display comprises a two-dimensional array of such single display units. FIG. 1A, for example, illustrates a partial sectional view of a monolayer black and white gyricon display according to the present invention where the gyricon display 2 comprises a plurality of display units 4. Each display unit 4 has an optical lens 38 on top of a particle 6.

3. Method of Manufacture

To make a display in accordance with the present invention, a substrate 9 containing cavities that have surfaced openings must first be made. The display in the Crowley patent does not have a substrate 9 containing cavities and is therefore not suitable for implementing the improvement according the present invention. In addition, the display in the Crowley patent has two other potential problems. First, the display package is environmentally and mechanically sealed only around the perimeter of the display. This results in the package being susceptible to cracking as may result from wear and tear; in this instance, a single crack would be adequate to enable all of the dielectric oil to drain or evaporate away, thereby disabling the function of the display. Additionally, the package is susceptible to buckling, and the elastomer-particle film can sag or slide out of position because of gravity (especially when held vertically for long periods of time, such as for display signs). This is because the mechanical support for the package is primarily the thin polymer films on the front and back sides, and because the reinforcement of these films occurs only where they are bonded together along the periphery.

Elastomer matrix structures in prior art may be used for the purpose of the present invention if the elastomer, with or without the combination of particles, has a surface structure that facilitates lens forming. In most conventional elastomeric structures, however, the cavities and particles are largely enclosed and located inside the elastomer and therefore have no surface openings, making it difficult to fabricate the lens structure of this application. In addition, these elastomer matrix structures have cavities that are randomly formed with irregular shapes and locations. Where each cavity represents a pixel or subpixel, there must be proper indexing or registration in the alignment between the addressing electrodes and each cavity, making the process of adding the auxiliary optical elements difficult and consequently resulting in high costs for making a display.

U.S. Patent No. 5,777,782 to Sheridan is an example for a structure with such limitations.

An exemplary preferred method of making a pre-formed substrate **9** containing cavities **33** is described in details in the commonly-owned U.S. patent application titled "Post and Pocket Microstructures for Movable Particles Having an Optical Effect" and filed concurrently (Attorney Docket Number M507.12-14). The disclosure of the above-identified patent application is hereby incorporated herein by reference.

The concepts and the methods of manufacture disclosed in that application may be used to preform a substrate **9** containing cavities **33** that have proper geometric shapes and pattern to accommodate both optically anisotropic particles **6** such as gyricon particles and assisting optical lens **38**. As described in that application, the post and pocket microstructures have many other advantages. Particularly, the pocket and post structure has a surface structure such as the cavities which are open from the top during manufacturing. Such a structure accommodates the process of adding or directly forming an optical lens **38** on the substrate. Additionally, where a dielectric fluid is used such as in a gyricon display using rotatable particles, the dielectric fluid does not need to diffuse through an elastomer. This allows a much greater variety of dielectric fluids to be used than in the case for the swollen elastomer sheets.

With an above preferred preformed substrate **9**, assisting optical lens **38** may be included in the following two different ways: 1) preforming the assisting optical lens **38** separately (e.g., formed on a top plate that also has the addressing electrodes) and then placing them over the substrate **9**, and, 2) forming the assisting optical lens **38** directly or integrally on the elastomer substrate **9**. As used in the present application, a process of "directly forming in assisting optical element on the substrate" means a process that involves more than simple placement of a pre-

formed assisting optical element on the substrate or making necessary physical connections between an assisting optical element and the substrate. However, directly forming the lenses 38 on the substrate 9 is preferred for the following reasons: 1) when the pre-formed substrate disclosed in the above identified patent application is used, fabrication of the substrate and fabrication of the assisting optical elements (e.g., lens 38) may be made one single integrated manufacturing process to improve efficiency and lower the cost; and 2) integrated manufacturing process additionally provides an intrinsic solution to the difficult problem of exact indexing or registration between each lens 38 and its corresponding display unit 4.

Assisting optical elements other than lenses 38 may also be used to enhanced the contract of a display. For example, as described in details in the commonly-owned U.S. patent application titled "Microstructures with Assisting Optical Elements to Enhance an Optical Effect" and filed concurrently (Attorney Docket Number M507.12-16), a reflective corona shouldering a particle, creates an appearance of the surface of the particle larger than the actual size of the surface through reflection of the light from surface, given that the reflective corona is larger than the particle. A reflective corona may simply be made of metalized reflective surfaces, or alternatively formed by using the principle of total internal reflection in which a total reflection is created at an interface of two different materials at certain incident angles of the light, even though the interface is not made of a material which is highly reflective in ordinary sense.

The optical lens structure in accordance with the present invention offers an alternative to the above assisting optical elements. Besides being optically distinctive, the optical lens structure also offers an alternative way of fabricating assisting optical elements on a display. For example, because the lenses 38 are formed subsequent to the placement of the display elements 6 (such as gyricon particles) into the substrate, the lenses 38 may be formed directly on top of the display particles 6, resulting in a lens structure automatically conforming to the

geometric shape of the particles, a benefit in addition to the above-discussed automatic indexing.

Converging lenses 38 can be made by conventional methods, such as compression molding. Conventional methods, if used to pre-form the lenses separately, will be less preferable due to the difficulties to register each lens 38 with a corresponding cavity 33.

With reference to FIG. 3 and FIG. 4, there is described herein a preferable method of making converging lenses 38 using a self-forming micro-lens array by self-forming micro-lens film 46. An array of micro-lenslets 38 can be manufactured from transparent thermoplastic polymer which is pressed onto an array of holes (cavities 33 as applied in the present invention).

In FIG. 3, a plate assembly 42 comprises a high temperature backing plate 44, a low temperature lens forming layer 46 and a thin high temperature membrane 48. The backing plate 44 is a rigid material which has a high melting temperature. The low temperature lens forming layer 46 is a polymer which has a low melting temperature such as an ethylene-vinyl acetate copolymer resin (EVA). The thin high temperature membrane 48 is an elastic material which has a high melting temperature such as a polyvinylidenechloride type resin (PVDC). The plate assembly 42 is placed over a two-dimensional array of display units 4.

FIG. 3 and FIG. 4 illustrate how a two-dimensional array of micro-lenses 38 is formed from the lens-forming layer 46. In FIG. 3, the plate assembly 42 is placed over a two-dimensional array of display units 4. Heat and pressure are then applied to the plate assembly 42. While the high temperature backing plate 44 and the high temperature membrane 48 withstand the temperature, essentially all of the lower melt temperature lens-forming material 46 is melted. The pressure deforms the membrane 48 (but does not substantially deform the backing plate 44 as the plate 44 is rigid) and pushes the membrane 48 into the cavities 33. Since the

membrane 48 is withheld at top perimeter edges 37 of the cavities 33 but pushed into each cavity 33 in the middle, the membrane 48 is contoured into a spherical surface (lens 38) in each cavity 33. At the same time, the melt lens-forming material 46 flows in response to both gravity and the pressure exerted by the topplate 44.

- 5 The flow of melt lens-forming material 46, however, is constrained at the bottom by the contoured and strained membrane 48 due to surface tension. The final result is a steady equilibrium state of pressure, forming a spherical lens 38.

- Only a minimum pressure and temperature is preferred. As the pressure increases, all lens-forming material 46 flows into the cavities 33 and the backing plate 44 will eventually come in contact with the top perimeter 37 of the cavities 33. This condition will prevent further flow of the lens-forming material 46. As a result, further pressure only results strain on the structure and contributes nothing in the lens making.

- The temperature should higher than the melting temperature of the lens-forming material 46 but less than the melting temperature of the top-plate 44, membrane 48 and the substrate 4. A temperature higher than the minimum melting temperature of the lens-forming material 46 will only result in a faster process of equilibrium to a limited degree, and is usually unnecessary or even harmful because too high a temperature may lead to difficulties in operation.

- 20 In the above process, the focal length of the lenses $F = (H^2 + A^2) / 2H$, where H is the thickness of the lens 38 at the center as shown in FIG. 4, while A is the diameter of the top perimeter opening 37 (full view not shown) of the cavity 33. H itself is determined by the total volume of each lens V according to the equation $V = 1/6\pi H (3A^2 + H^2)$. That is, for a given V and A, the value of H can be readily determined by solving the above equation. If the lens-forming layer 46 has a uniform thickness T, each unit cell of the array will have a precise volume V of lens-forming material associated with it. For example, if the top opening of each

cavity has an area of A^2 (full view not shown), each unit cell will have the volume $V = TA^2$ of lens-forming material associated with it. Therefore, focal length F of the lenses **38** is ultimately determined by T and A and hence easily controlled.

As applied to the present invention, the uniformity of the focal length
5 is not crucial as long as each lens has a sufficient enlarging effect. The actual range of focal length of the lenses **38**, however, is significant and must be controllable in the process of manufacturing because a proper range is determined according to the size of the cavities **33** so that the converging lenses **38** have enough enlarging effect to increase the contrast yet do not over-enlarge to cause blurring and hence decrease
10 the resolution.

Once the lens array **38** is formed, the backing plate **44** may be separated from array of cavities **4** or may remain adhered. The lens array **38** may also be separated from the array of cavities **4** and used for other purposes. In the present invention, however, the lens array **38** and the array of cavities **4** are kept
15 together, resulting in intrinsic registration.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of invention. All U.S. patents referred in this disclosure are incorporated by reference herein.